KUNGL TEKNISKA HÖGSKOLAN

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International Master Program in System-on-Chip Design

Hardware redundancy

Techniques for fault tolerance

- Fault masking “hides” faults that occur. Do not require detecting faults, but require containment of faults (the effect of all faults should be local)
- Another approach is to first to detect, locate and contain faults, and then to recover from faults using reconfiguration

Redundancy

- hardware redundancy
  - 2nd CPU, 2nd ALU, ...
- software redundancy
  - validation test...
- information redundancy
  - error-detecting and correcting codes, ...
- time redundancy
  - repeating tasks several times, ...

Example

- FT digital filter
  - acceptance test [0 - 255]
    - SW: detect overflow
    - HW: memory for test
    - time: to execute test
  - transients: via re-execution
    - time to re-execute

Redundancy (5)

- NOTHING FOR FREE!
- costs
  - HW: components, area, power, ...
  - SW: development costs, ...
  - information: extra HW to code / decode
  - time: faster CPUs, components
- trade-off against increase in dependability

Types of redundancy

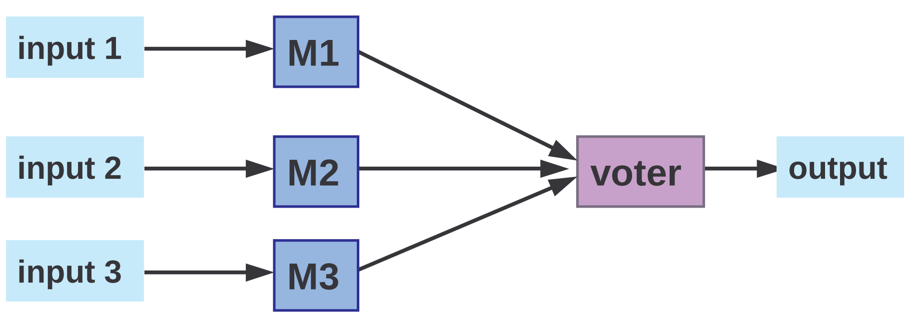
- hardware redundancy
- information redundancy
- software redundancy
- time redundancy

HW redundancy: overview

- passive redundancy techniques
  - fault masking
- active redundancy techniques
  - detection, localisation, containment, recovery
- hybrid redundancy techniques
  - static + dynamic
  - fault masking + reconfiguration

Passive HW redundancy

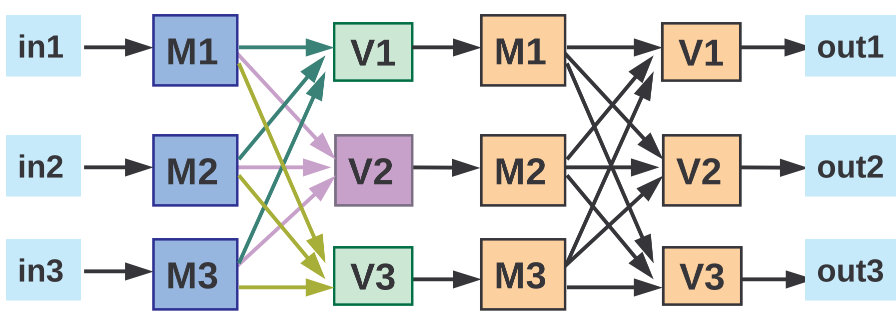
Triple Modular Redundancy (TMR)



Passive HW redundancy

- Triple Modular Redundancy (TMR)
  - 3 active components
  - fault masking by voter
- Problem: voter is a single point of failure

Passive HW redundancy



restoring organ

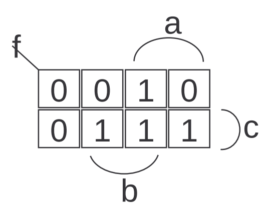
Passive HW redundancy

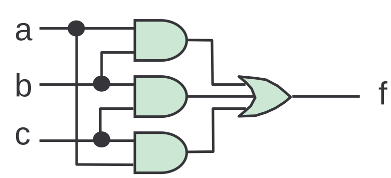
- N-modular redundancy (NMR)
  - N active components (N A)
  - N odd, for majority voting
  - tolerates $\lfloor N/2 \rfloor$ faults
- example Apollo
  - N=5
  - 2 faults can be tolerated (masked)

HW voting

hardware realisation of 1-bit majority voter

f = ab + ac + bc





n-bit majority voter: n times 1-bit

requires 2 gate delays

SW voting

- Voting can be performed using software
- voter is software implemented by a microprocessor
- voting program can be as simple as a sequence of three comparisons, with the outcome of the vote being the value that agrees with at least on on the other two

HW vs. SW Voting

- HW: fast, but expensive
  - 32-bit voter: 128 gates and 256 flip-flops
  - 1 TMR level = 3 voters
- SW: slow, but more flexible
  - use existing CPUs

Problem with voting

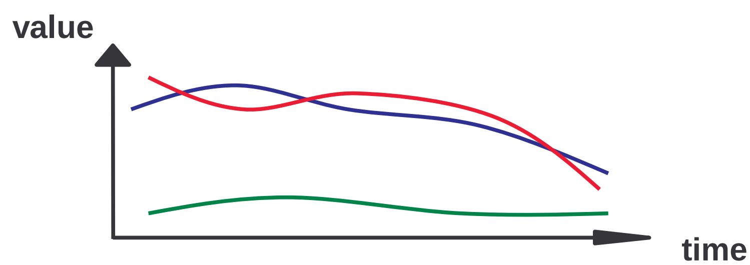
- Major problem with practical application of voting is that the three results may not completely agree
  - sensors, used in many control systems, can seldom be manufactured so that their values agree exactly
  - analog-to-digital converter can produce quantities that disagree in the least significant bits

Problems with voting

- (1) When values that disagree slightly are processed, the disagreement can grow larger
  - small difference in inputs can produce large differences in outputs
- (2) A single result must ultimately be produced
  - potential point where one failure can cause a system failure

How to cure problem 1

- Mid-value select technique
  - choose a value from the three which lies between the other two



How to cure problem 1

- Ignore the least-significant bits of data
  - disagreement which occurs only in the least-significant bits is acceptable
  - disagreement which affects the most-significant bits is not acceptable and must be corrected

Types of HW redundancy

- static techniques (passive)
  - – fault masking
- dynamic techniques (active)
  - – detection, localisation, containment and recovery
- hybrid techniques
  - – static + dynamic
  - – fault masking + reconfiguration

Active HW redundancy

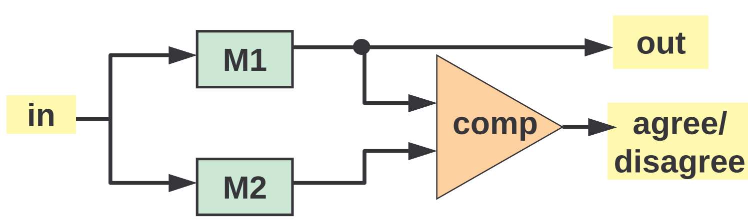
- dynamic redundancy
  - – actions required for correct result
    - detection, localization, containment, recovery
    - no fault masking
  - – does not attempt to prevent faults from producing errors within the system

Active HW redundancy

- most common in applications that can tolerate temporary erroneous results
  - satellite systems - preferable to have temporary failures that high degree of redundancy
- types of active redundancy:
  - duplication with comparison
  - standby sparing
  - pair-and-a-spare
  - watchdog timer

Duplication with comparison

- Two identical modules perform the same computation in parallel and their results are compared



Duplication with comparison

- The duplication concept can only detect faults, not tolerate them
  - there is no way to determine which module is faulty

Duplication with comparison

- Problems:
  - if there is a fault on input line, both modules will receive the same erroneous signal and produce the erroneous result
  - comparator may not be able to perform an exact comparison
    - synchronisation
    - no exact matching
  - comparator is a single point of failure

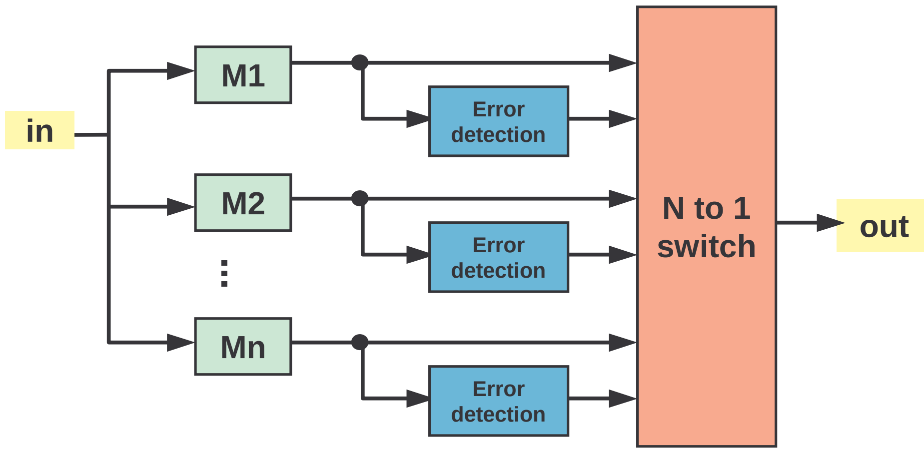
Implementation of comparator

- In hardware, a bit-by-bit comparison can be done using two-input exclusive-or gates
- In software, a comparison can be implemented a a COMPARE instruction
  - commonly found in instruction sets of almost all microprocessors

Standby sparing

- One module is operational and one or more serve as stand-bys, or spares
- error detection is used to determine when a module has become faulty
- error location is used to determine which module is faulty
- faulty module is removed from operation and replaced with a spare

Standby sparing

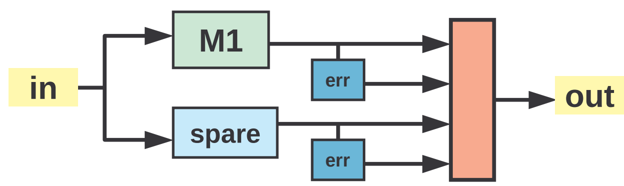


Switch

- The switch examines error reports from the error detection circuitry associated with each module
  - if all modules are error-free, the selection is made using a fixed priority
  - any module with errors is eliminated from consideration
  - momentary disruption in operation occur while the reconfiguration is performed

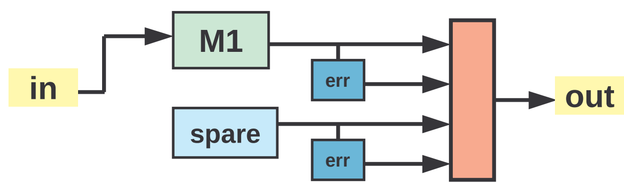
Hot standby sparing

- In hot standby sparing spares operate in synchrony with on-line module and are prepared to take over any time



Cold standby sparing

- In cold standby sparing spares are unpowered until needed to replace a faulty module



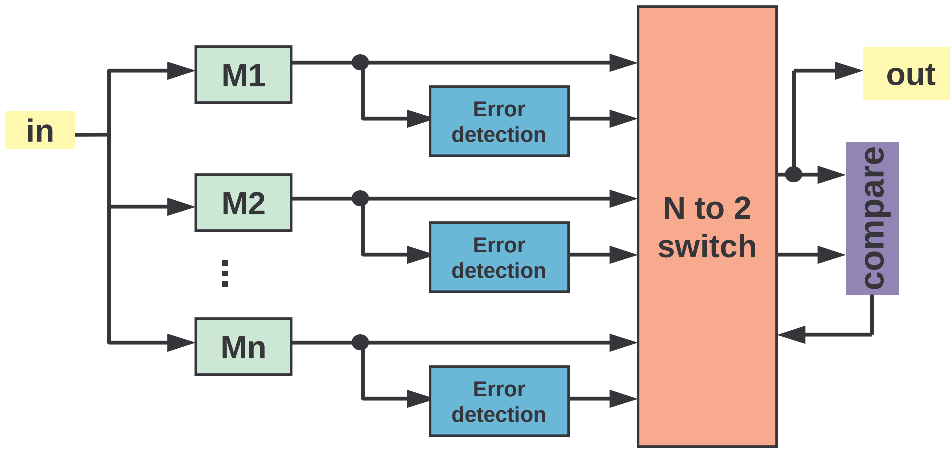
+ and - of cold standby sparing

- (-) time is required to bring the module to operational state
  - time to apply power to spare and to initialize it
  - not desirable in applications requiring minimal reconfiguration time (control of chemical reactions)
- (+) spares do not consume power
  - desirable in applications where power consumption is critical (satellite)

Pair-and-a-spare technique

- Combines standby sparing and dublication with comparison
- like standby sparing, but two instead of one modules are operated in parallel at all times
  - their results are compared to provide error detection
  - error signal initiates reconfiguration

Pair-and-a-spare technique



Pair-and-a-spare technique

- As long as two selected outputs agree, the spares are not used
- If they disagree, the switch uses error reports to locate the faulty module and to select the replacement module

Watchdog timer

- watchdog timer
  - must be reset an on a repetitive basic
  - if not reset - system is turned off (or reset)
  - detection of
    - crash
    - overload
    - infinite loop
  - frequency depends on application
    - aircraft control system - 100 msec
    - banking - 1 sec

HW redundancy: overview

- static techniques (passive)
  - fault masking
- dynamic techniques (active)
  - detection, localisation, containment, recovery
- hybrid techniques
  - static + dynamic
  - fault masking + reconfiguration

Hybrid HW redundancy

- combines
  - static redundancy
    - fault masking
  - dynamic redundancy
    - detection, location, containment and recovery
- very expensive but more FT

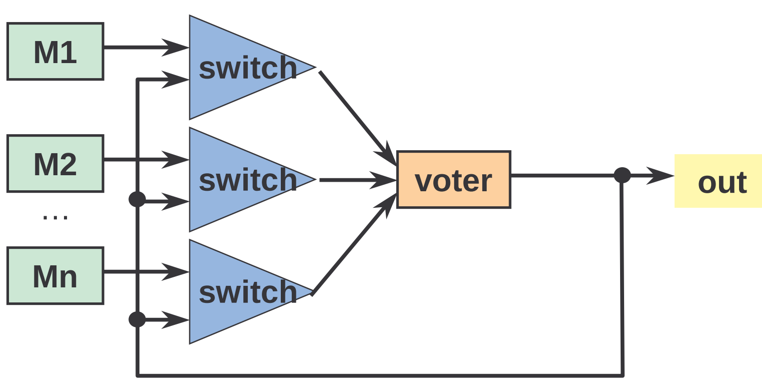
Types of hybrid redundancy

- Self-purging redundancy
- N-modular redundancy with spares
- Triple-duplex architecture

Self-purging redundancy

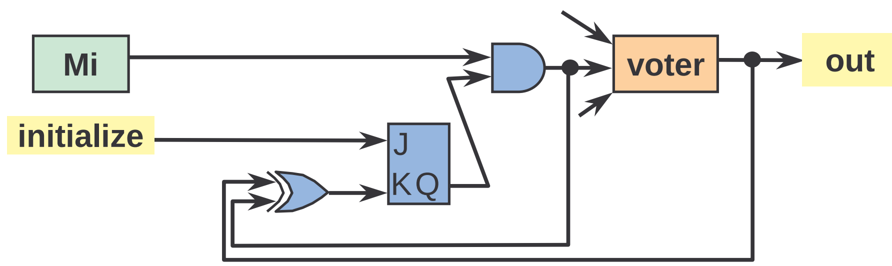
- All units are actively participate in the system
- each module has a capability to remove itself from the system if its faulty
  - very attractive feature: maintenance personnel can disable individual modules and replace them without interrupting the system

Self-purging redundancy

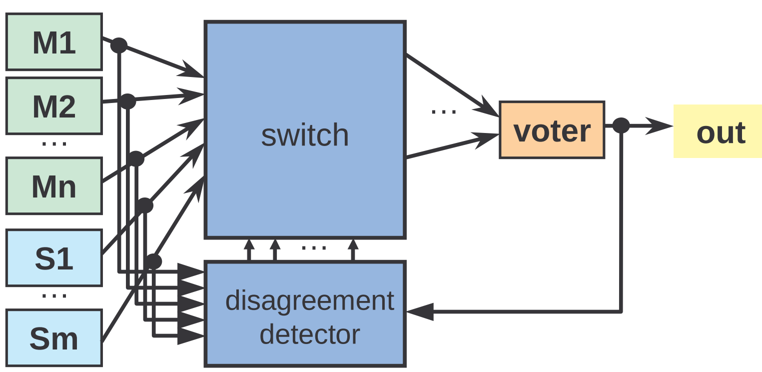


Basic structure of a switch

- Is output of a module disagrees with the output of the system, its contribution to the voter is forced to be 0 (threshold voter)



N-modular redundancy with spares



NMR with spares

- System remains in the basic NMR configuration until the disagreement vector determines a fault
- the output of the voter is compared to the individual outputs of the modules
- module which disagrees is labeled as faulty and removed from the NMR core
- spare is switched to replace it

NMR with spares

- The reliability is maintained as long as the pool of spares is not exhausted
- 3-modular redundancy with 1 spare can tolerate 2 faults
- to do it in a passive approach, we would need to have 5 modules

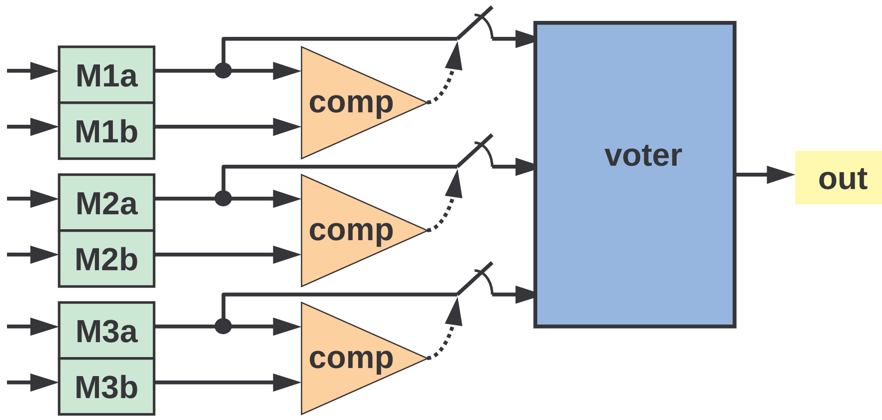
Sift-out modular redundancy

- Using N active modules
- each module's output is compared (pairwise) to the remaining modules' outputs
- the module which is identified as faulty is not allowed to to influence the output

Triple-duplex architecture

- Combines duplication with comparison and triple modular redundancy

Triple-duplex architecture



Triple-duplex architecture

- TMR allows faults to be masked
  - performance without interruption
- duplication with comparison allows faults to be detected and faulty module removed from voting
  - removal of faulty module allows to tolerate future faults
- two module faults can be tolerated

Summary

- application-dependent choice
  - critical-computation - momentary erroneous results are not acceptable
    - passive or hybrid
  - long-life, high-availability - system should be restored quickly
    - active
  - very critical applications - highest reliability
    - hybrid